Active Control of Instabilities in Laminar Boundary-Layer Flow – Part II: Use of Sensors and Spectral Controller

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Abstract

This study focuses on the suppression of instability growth using an automated active-control technique. The evolution of 2D disturbances that are spatially growing in a flat-plate boundary layer are computed with a spatial DNS code. A controller receives wall sensor information (pressure or shear) as input and provides a signal that controls an actuator response as output. The control law assumes that wave cancellation is valid. The results indicate that a measure of wave cancellation can be obtained for small- and large-amplitude instabilities without feedback; however, feedback is required to optimize the control amplitude and phase for exact wave cancellation.

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Introduction

This second study focuses on the suppression of instability growth using an automated active-control technique. This automated approach is the next logical step based on previous experimental and computational studies reviewed by Joslin, Erlebacher, and Hussaini[1] and by Thomas,[2] in which the control was in the form of wave cancellation. The wave-cancellation method assumes that a wavelike disturbance can be linearly cancelled by introducing another wave with a similar amplitude but that differs in phase. Both experimental and computational results have demonstrated that two-dimensional (2D) Tollmien-Schlichting (TS) waves can be superposed upon 2D waves in such a way as to reduce the amplitudes in the original waves under the presumption of wave cancellation. Joslin et al.[1] have definitively shown that flow control by wave cancellation is the mechanism for the observed phenomena.

Although the present active-control approach is demonstrated here for a 2D instability test case, the ultimate goal of this line of research is to introduce automated control to external flow over an actual aircraft or to any flow which has instabilities that require suppression.

Toward this goal, the present study computes the evolution of 2D disturbances that are spatially growing in a flat-plate boundary layer. In this study, a controller receives sensor information as input and provides a signal that controls an actuator response as output. The nonlinear computations consist of the integration of the sensors, actuators, and controller as follows: the sensors will record the unsteady pressure or shear on the wall; the spectral analyzer (controller) will analyze the sensor data and prescribe a rational output signal; the actuator will use this output signal to control the disturbance growth and stabilize the instabilities within the laminar boundary layer. This scenario is shown in Fig. 1. Although a closed-loop feedback system could be implemented (using an additional sensor downstream of the actuator) to fully automate the control and lead to an exact cancellation of the instability, the feedback will not be introduced here due to the added computational expense of the iterative procedure.

Numerical Techniques

The nonlinear, unsteady Navier-Stokes equations are solved by direct numerical simulation (DNS) of disturbances, which evolve spatially within the boundary layer. The spatial DNS[3,4] approach involves spectral and high-order finite-difference methods and a three-stage Runge-Kutta method[5] for time advancement. The influence-matrix technique is employed to solve the resulting pressure equation (Helmholtz-Neumann problem).[6,7] Disturbances are introduced into the boundary layer by unsteady suction and blowing through a slot in the wall, where the slot has a length $8.57\delta_o^*$. At the outflow boundary, the buffer-domain technique of Streett and Macaraeg[8] is used.

The equations are nondimensionalized with the free-stream velocity U_∞, the kinematic viscosity ν, and the inflow displacement thickness δ_o^*. The Reynolds number becomes $R = U_\infty \delta_o^* / \nu$, and the frequency is $\omega = \omega^* \delta_o^* / U_\infty$.

Control Method

Here, the term "controller" refers to the logic that is used to translate sensor-supplied data into a response for the actuator, based on some control law. For the present study, a spectral controller requires a knowledge of the distribution of energy over frequencies and spatial wave numbers. For this automated controller system, a minimum of two sensors must be used to record either the unsteady pressure or unsteady shear at the wall. Here, the first sensor is located $57.88\delta_o^*$ downsteam of the inflow, and the second sensor is located $2.33\delta_o^*$ downsteam of the first sensor. By using Fourier theory, this unsteady data can be transformed via

$$f(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \tag{1}$$

where $f(t)$ is the signal and ω is the frequency. This transform yields an energy spectrum that indicates which frequencies exist in the signal and how much relative energy each frequency contains.

The largest Fourier coefficient indicates the frequency that will be used to control the instability, although the largest growth rate can be used instead of largest coefficient. The information from the two sensors is used to obtain estimates of both spatial growth rates and phase via the relation

$$\alpha = \frac{1}{A}\frac{dA}{dx} \tag{2}$$

This temporal and spatial information is then substituted into the assumed control law, or wall-normal velocity boundary condition,

$$v_s(x,t) = 1.5 v_w \times [p_w^1 e^{i(\omega+\phi_t)t+\alpha x_s} + c.c.] \tag{3}$$

where p_w^1 is the complex pressure (or shear) for the dominant frequency mode (or largest growth-rate mode) at the first sensor, ω is the dominant mode determined from equ. (1), ϕ_t is the phase information, t is the time, α is the growth-rate and wave number information calculated from equ. (2), and x_s is the distance between the first sensor and the actuator (which is $4.67\delta_o^*$ in length and located approximately 3 wavelengths downstream of the disturbance forcing).

This control law is used only for this feasibility study. Aspects of formal optimal-control theory and artificial neural-network algorithms are currently being tested by the authors for use in a subsequent study.

Numerical Experiments

For this study, we are not concerned with the method by which disturbances are ingested into the boundary layer; the underlying assumption here is that natural transition involves some dominant disturbances that can be characterized by waves. In a subsequent study, we will explore controlling transition consisting of either random unsteady or three-dimensional nonlinear and arbitrary instabilities. Here, the instabilities are assumed to be characterizable by discrete frequencies within the spectrum.

For the computations, the grid has 661 streamwise and 61 wall-normal points. The far-field boundary is located $75\delta_o^*$ from the wall, and the streamwise distance is $308\delta_o^*$ from the inflow, which is equal to approximately 11 TS wavelengths. The disturbance frequency is $Fr = \omega/R \times 10^6 = 86$, and the Reynolds number is $R = 900$ at the inflow. (The streamwise range of the computations and the relative sensor and actuator are located within the unstable region of the linear stability neutral curve.) A time-step size of 320 steps per period is chosen for the three-stage Runge-Kutta method. To complete a 2D simulation, 0.9 hr on the Cray Y/MP are required with a single processor. (Refer to ref. 3 for details on accuracy issues with grid refinement.)

A small-amplitude disturbance ($v_f = 0.0001$) is forced at the inflow and controlled via the automated control law without feedback. Figure 2 shows the TS wave amplitudes with downstream distance for the present results compared with the control case ($v_w = 0.6v_f$) of Joslin, Erlebacher, and Hussaini[1] and the uncontrolled wave. The present results demonstrate that a measure of wave cancellation can be obtained from the automated system prior to initating feedback; however, feedback is necessary to optimize the control amplitude and phase for exact cancellation of the disturbance.

Figure 3 shows a similar comparison for the control of a large-amplitude disturbance ($v_f = 0.3$). Again, the automated control can clearly obtain a degree of wave cancellation for large-amplitude instabilities without optimization and without exciting the harmonics of the fundamental wave. These test cases demonstrate that automated control can be effective with the presumption of discrete frequency instability waves.

Conclusions

Full Navier-Stokes simulations were conducted to determine the feasibility of automating the control of wave instabilities within a flat-plate boundary layer with sensors, actuators, and a spectral controller.

The results indicate that a measure of wave cancellation can be obtained for small- and large-amplitude instabilities without feedback; however, feedback is required to optimize the control amplitude and phase for exact wave cancellation.

This study is only the second in a series aimed at suppressing the instabilities that lead to transition within an otherwise laminar boundary layer with unsteady flow control. Follow-on research will focus on coupling optimal control theory with the Navier-Stokes equations to devise a control methodology without distinct control laws. This methodology focuses on the minimization of the wall shear at a prescribed region downstream of the actuator. This flow control could lead to suppression of arbitrary instabilities in a laminar boundary layer, drag reductions in a turbulent boundary layer, or enhanced lift by seperation control.

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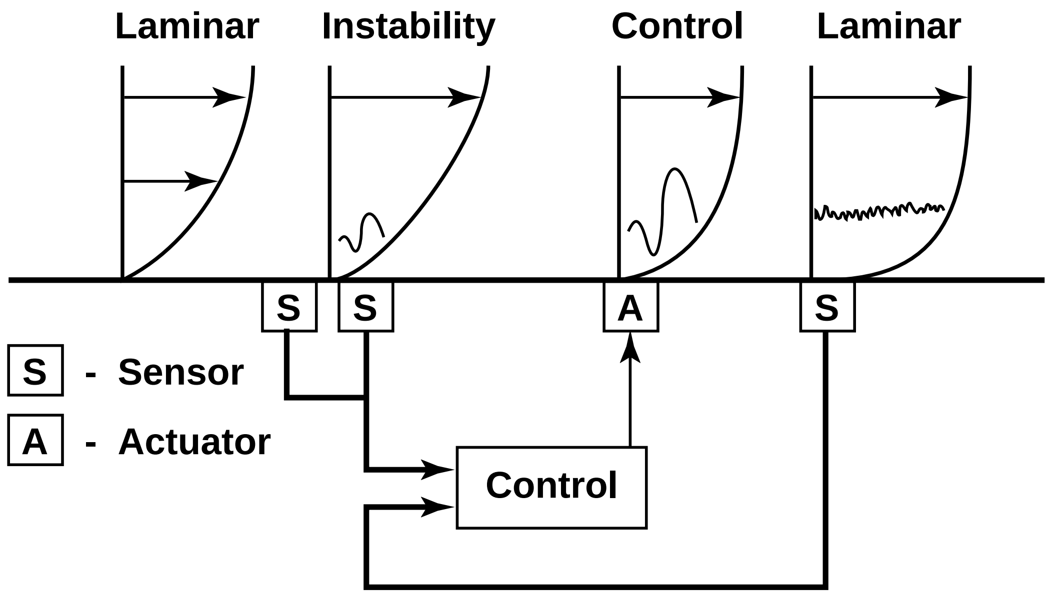

Figure 1. Schematic of active control with "wave cancellation."

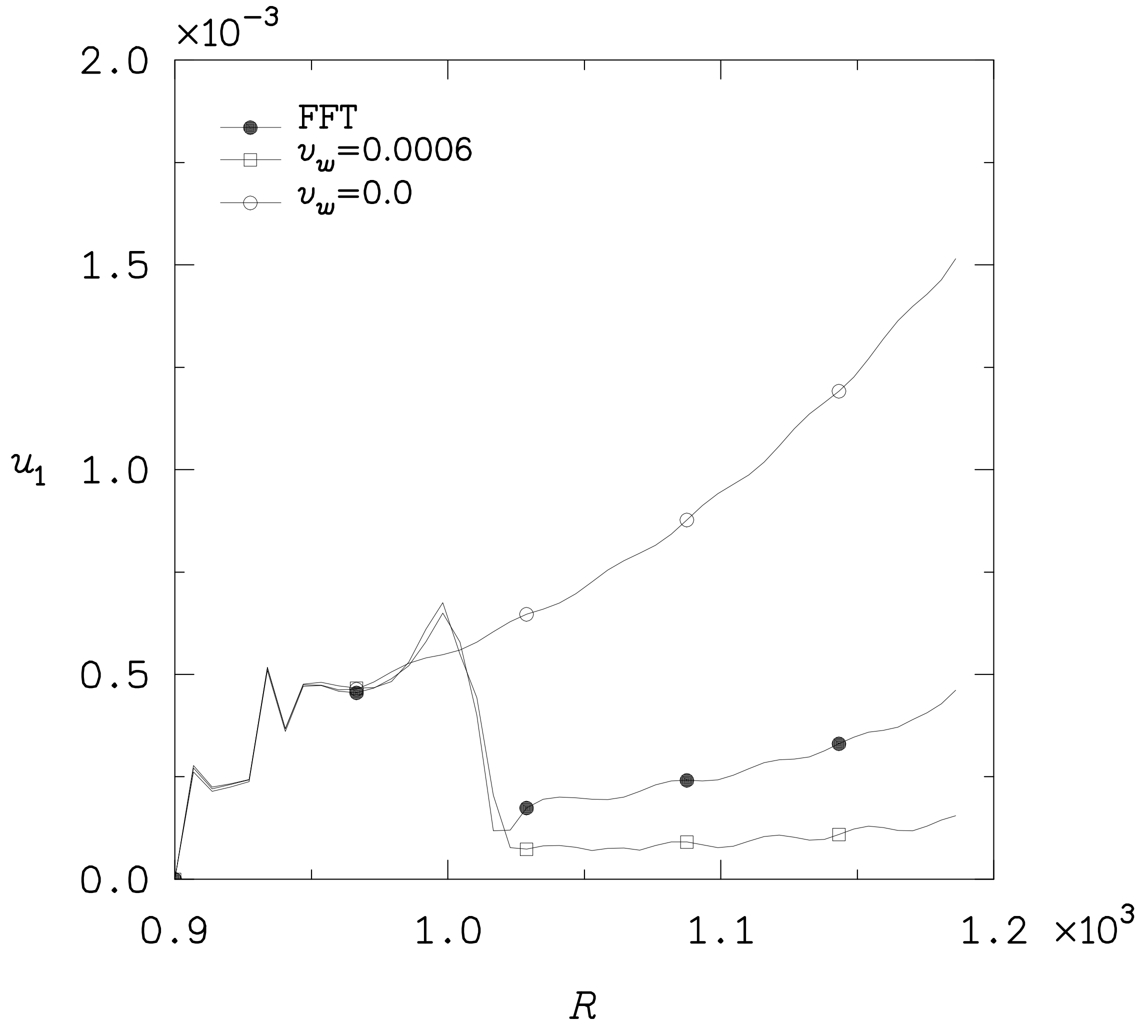

Figure 2. Active control of small-amplitude TS waves in flat-plate boundary layer.

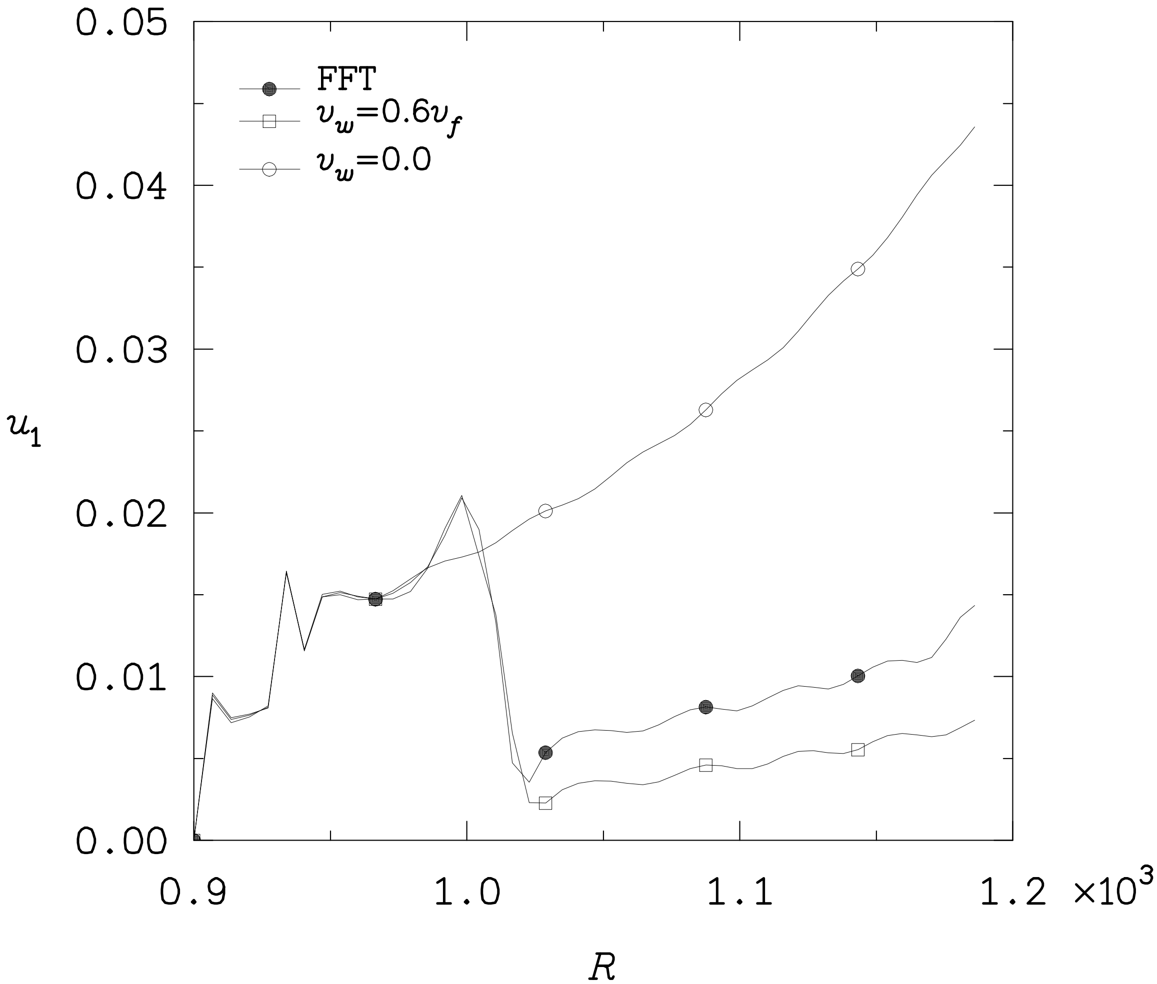

Figure 3. Active control of large-amplitude TS waves in flat-plate boundary layer. (v_f = 3%).